ELECTRON CLOUD IN LINEAR COLLIDER DAMPING RINGS*

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Abstract

The positron damping rings for a future linear collider will operate at energies and with beam currents where electron cloud effects could be a significant problem. Both coupled-bunch and single-bunch instabilities would adversely affect damping ring performance, by limiting the stored current, or by increasing the transverse bunch size; either effect would reduce the luminosity of the collider. Recent work has estimated, for TESLA and the NLC, the thresholds and growth rates of instabilities driven by the electron cloud, with results from simulation and analytical investigation in reasonable agreement. We review the results, which strongly suggest that serious consideration needs to be given to ways in which the effects of electron cloud can be mitigated.

1 DAMPING RINGS

The damping rings for a linear collider are designed to reduce the 6-D emittance of the beams from the sources, before acceleration in the main linacs. Luminosity requirements and main linac parameters drive the storage ring parameters; in particular, the damping rings are designed for high currents and moderate energies, and they are therefore susceptible to various instabilities. Observations of electron cloud effects at other storage rings operating in broadly comparable parameter regimes have led to concerns that positron damping rings will be limited by instabilities driven by the electron cloud. Here we present estimates suggesting that electron cloud could indeed be a problem, and that attention should be given to strategies for preventing the cloud build-up. We consider damping rings for the NLC [1] and TESLA [2], since these are the most mature designs for a future linear collider.

Some relevant parameters for the NLC Main Damping Ring (MDR), NLC Positron Pre-Damping Ring (PDR), and the TESLA Positron Damping Ring are compared with those of some operating positron storage rings in Table 1. In TESLA, the long bunch train, and the bunch-by-bunch injection/extraction in the rings, leads to the need for a very large damping ring circumference of 17 km, compared to the few hundred meters of the NLC damping rings. A specific feature of the TESLA design is that the beam is fully coupled in the long straight sections, to overcome space-charge effects.

Some simulations of electron cloud in the NLC have been performed, aimed mainly at determining the cloud density and distribution under various conditions, although initial estimates of the long-range wake field have also been made. The results of these simulations are reported elsewhere [3]; here, we use simple analytic models to estimate the likely severity of the instabilities driven by the electron cloud. Our aim in this approach is to try and develop an understanding of the dependence of the various instability modes on the significant parameters. As a simple check, we apply the models to some operating positron storage rings, to see whether the expectations are consistent with observations.

2 OUTLINE OF MODELS

We are concerned with the instabilities driven by the electron cloud, rather than with the production of the cloud. Although the damping rings include antechambers to allow the absorption of synchrotron radiation at photon stops, the secondary electron yield of the vacuum chamber walls can lead to a build-up of the cloud from a small number of seed electrons, produced e.g. from residual gas ionization. Although the rate of electron production may be small, simulations suggest that the saturation density of the cloud may be estimated using the neutralization condition:

$$n_0 = \frac{N_b}{\pi b^2 s_b}$$

Table 1: Parameters of NLC and TESLA damping rings compared to some other positron storage rings.

	NLC MDR	NLC PDR	TESLA	KEK-B LER	PEP-II LER	DAΦNE	HERA-e
Energy /GeV	1.98	1.98	5	3.5	3.1	0.51	12
Circumference /m	300	231	17000	3000	2200	98	6300
Bunch charge /10^{10}	0.75	0.75	2	3.3	9	5.4	3
Betatron tunes	27, 11	11, 5.5	76, 41	46, 46	20, 20	5, 5	50
Synchrotron tune	0.0035	0.011	0.066	0.015	0.03	0.01	50
RMS beam sizes /μm	200, 20	150, 230	60, 80	420, 60	1400, 200	1700, 95	110, 11
Bunch length /mm	3.6	5.2	6.0	4	13	25	5
Mom^m compaction	0.3×10^{-3}	2×10^{-3}	0.1×10^{-3}	0.2×10^{-3}	0.1×10^{-3}	0.03	0.5×10^{-3}
Bunch separation /m	0.42	0.42	6.0	2.4	2.5	1.6	29
Beam pipe radius /mm	16	36	50	47	45/25	35	20/40

where n_0 is the cloud density at saturation, N_b the number of positrons per bunch, πb^2 the cross-sectional area of the vacuum chamber, and s_b the bunch separation. We further assume that the distribution of the cloud is Gaussian, with width equal to that of the beam. Although these assumptions neglect the complicated dynamics of the cloud, we feel they are sufficient for our purposes of estimating whether a storage ring is operating in a regime where electron cloud effects will be significant.

The electron cloud will couple the dynamics of particles in the beam over both a short range (i.e. within a bunch) and a long range (i.e. between bunches). Although the effects are in some ways similar to electromagnetic transverse wake fields arising, for example, in cavities in the vacuum chamber, there are important differences. In the case of an electromagnetic wake, the field seen be a particle at the tail of a bunch is simply the sum of the fields generated by the preceding particles, so the wake may be represented by a Green's function. Since the electrons in the electron cloud are electrically charged, the wake from particles at the head of a bunch is affected by all subsequent particles, which also contribute their own wake. This means that the wake cannot be strictly represented by a Green's function. Nevertheless, one may consider the electrons in the cloud to oscillate in the field of a bunch (over a short range) or of the beam (over a long range), in which case the effect of the cloud is similar to that of a broad-band resonator. To allow us to apply standard methods to arrive at estimates of thresholds and growth rates, we shall model the wake of the cloud by that of a broad-band resonator. This is the approach taken, for example, by Ohmi, Zimmermann and Perevedentsev [4] and by Heifets [5,6]; much of our analysis follows their work.

3 SHORT-RANGE WAKE

We can first attempt to apply the standard head-tail theory. We write the wake function in units of m^{-2} for $z<0$ as:

$$W_1(z) = \frac{cR_s}{Q} \exp\left(-\frac{\omega_c z}{2cQ}\right) \sin\left(\frac{\omega_c z}{c}\right) \qquad (1)$$

where the amplitude is given by [4]:

$$\frac{cR_s}{Q} = \frac{\gamma \omega_b^2 \omega_c}{\lambda_b r_e c^3} C \qquad (2)$$

Here, C is the circumference, and ω_b and ω_c are the oscillation frequencies of the bunch particles in the cloud, and the cloud particles in the bunch respectively, given by:

$$\omega_b^2 = \frac{\lambda_c r_e c^2}{\gamma(\sigma_x + \sigma_y)\sigma_y} \qquad \omega_c^2 = \frac{\lambda_b r_e c^2}{(\sigma_x + \sigma_y)\sigma_y}$$

where λ_b and λ_c are the line densities of particles in the bunch and the cloud, respectively, and r_e is the classical electron radius. The quality factor Q characterizes the

decoherence of the oscillations in the electron cloud initiated by a transverse displacement of particles in the beam. This factor may be estimated analytically [6], or fitted from simulation. One generally finds that Q is of the order 5, but the results of the single bunch instability estimate are insensitive to the exact value. Relevant quantities for NLC MDR and TESLA are given in Table 2.

Table 2: Short-range wake parameters.

Quantity	NLC MDR	TESLA
Cloud density /m^{-3}	2.2×10^{13}	4.2×10^{11}
Cloud frequency /s^{-1}	1.0×10^{12}	2.1×10^{11}
Bunch frequency /s^{-1}	2.8×10^{6}	1.6×10^{5}
Wake amplitude /m^{-2}	1.5×10^{8}	9.6×10^{6}
Quality factor	5	5

The frequencies of the synchrotron sidebands (in units of the synchrotron frequency) to the betatron frequency are given by the eigenvalues of the matrix:

$$M_{ll'} = l\delta_{ll'} - i\frac{N_b r_e c^2}{4\pi\gamma C\omega_\beta \omega_s}\frac{i^{l-l'}}{\sqrt{ll'}}\int_{-\infty}^{\infty}d\omega Z_1(\omega)\left(\frac{\omega\sigma_z}{\sqrt{2}c}\right)^{l+l'}\exp\left(-\frac{\omega^2\sigma_z^2}{c^2}\right)$$

where Z_1 is the impedance associated with the wake field (1), σ_z is the bunch length, and ω_β and ω_s are the betatron and synchrotron frequencies respectively. We have assumed that the bunch has a Gaussian distribution in longitudinal phase space, the chromaticity is zero, and we consider only the lowest radial mode. We have also assumed that the electron cloud distribution is Gaussian, with the same transverse widths as the bunch.
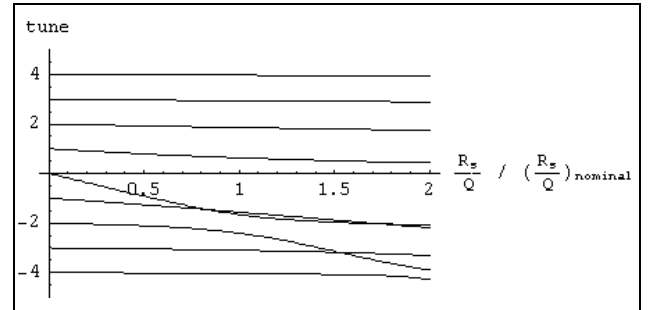

Figure 1: Synchrotron sideband tunes as a function of the electron cloud impedance, for the NLC MDR.
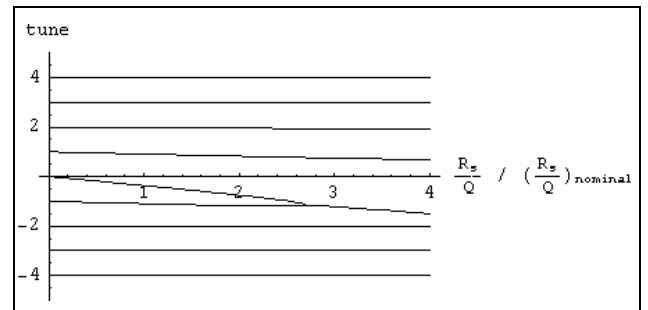

Figure 2: Synchrotron sideband tunes as a function of the electron cloud impedance, for the TESLA damping ring.

The tunes for some of the low-order synchrotron sidebands are shown in Figure 1 for the NLC MDR, and Figure 2 for TESLA (treating the beam as fully coupled through the entire lattice, and with the cloud density defined by a vacuum chamber radius of 50 mm).

In each case, the tune is shown as a function of the amplitude of the impedance, in units of the nominal impedance expected from (2). The coupling of a pair of modes indicates a complex value for the frequency of the sideband, and hence identifies the head-tail threshold. Given the approximations in the model, the graphs should be read only as being indicative of the proximity of the nominal operating conditions to the head-tail threshold; thus although it appears that TESLA could operate some way below the threshold, this should not be regarded as any kind of safety margin.

A feature of the tune shifts in the case of the NLC, is the narrow range over which the modes couple, before separating. This arises from the fact that the cloud frequency is large compared to the characteristic bunch frequency c/σ_z, i.e. electrons in the cloud perform many oscillations in the bunch during one bunch passage. In this situation it may be more appropriate to use a coasting beam model for the instability, rather than the head-tail theory. Kernel et al [7], reproducing earlier results by Ruth and Wang [8], have described a relevant model. The instability threshold bunch population is given by:

$$N_{th} = 4\sqrt{\frac{3}{2}} \frac{\gamma C \alpha \sigma_\delta \sigma_z \omega_q}{r_e c^2 \beta_y |Z_{eff}|}$$

where the effective impedance Z_{eff} is given by:

$$Z_{eff} = \frac{\sum_{p=-\infty}^{\infty} Z_1(\omega_p) \exp\left(-(\omega_p - \omega_q)^2 \sigma_z^2/c^2\right)}{\sum_{p=-\infty}^{\infty} \exp\left(-(\omega_p - \omega_q)^2 \sigma_z^2/c^2\right)}$$

$\omega_p = p\omega_0 + \omega_\beta$, and ω_q is chosen to maximize the real part of Z_{eff}. For the NLC MDR, we find that this gives a population of just under 10^{10} particles, again indicating that the nominal parameters place the ring close to the threshold.

As we have already mentioned, the above analysis assumes that the electron cloud distribution has the same widths as the bunch. Simulations suggest that the field of the bunch can have the effect of increasing the density on the beam axis by more than an order of magnitude [9]. In this case, the thresholds are lowered by a significant amount. Since the density enhancement takes place during the bunch passage, there is an incoherent tune shift that may be estimated by:

$$\Delta\nu_{x,y} = K_b \frac{\omega_b^2}{\omega_0^2 \nu_{x,y}}$$

where K_b is an enhancement factor ~10. For the NLC, the incoherent tune shift is of the order 0.2 (including an enhancement factor of 10), while for TESLA this approximation yields a value larger by an order of magnitude compared to the case of the NLC.

A further consideration for TESLA is the effect of electron cloud in the long straight sections, where there are no synchrotron oscillations. Here, the instability may resemble beam break-up, which is characterized by the parameter

$$Y = \frac{N_b r_e \beta_y}{4\gamma} \frac{cR_s}{Q}$$

with the linear growth rate for the dipole mode given by

$$\frac{1}{\tau} = \frac{c}{C} Y$$

For TESLA, the linear growth time is about 3 μs. This is short compared to the transit time for one of the long straight sections (about 25 μs), which means that beam break-up is indeed a possible instability mode.

4 LONG-RANGE WAKE

Although the density of the electron cloud decreases rapidly between bunches, as low energy electrons are absorbed on impact with the walls of the vacuum chamber, the cloud density can remain sufficiently high between bunch passages to couple the dynamics of one bunch to the next. We continue to use simple models to give rough estimates, to try and understand the dependence on various parameters. We neglect the fluctuation in the cloud density during bunch passages. Further, we assume that the electrons oscillate in the mean field of the beam; if the oscillation period is large compared with the bunch separation, this is likely to be a reasonable approximation. Note that we are concerned with electrons at relatively large amplitudes that perform slow oscillations in the beam; the short-range wake arises principally from electrons close to the beam, that perform rapid oscillations in the field of a single bunch.

We can write the equation of motion of an electron in the field of the beam:

$$\ddot{y} = -\frac{k^2}{y} \qquad k^2 = \frac{2N_b r_e c^2}{s_b}$$

where y is the transverse displacement of an electron with respect to the beam. With the initial conditions $y(0)=a$, $\dot{y}(0)=0$, this has the solution:

$$\sqrt{\ln\left(\frac{a}{y}\right)} = \text{Erf}^{-1}\left(\sqrt{\frac{2}{\pi}} \frac{k}{a} t\right)$$

Solving for $y(\pi/2\omega)=0$ where ω is the frequency of oscillation, we find:

$$\omega = \sqrt{\frac{\pi}{2}} \frac{k}{a}$$

Note that the frequency of oscillation is inversely proportional to the amplitude. The frequency spread will lead to a rapid decoherence of the oscillations.

As for the short-range wake, we assume that the wake field resulting from the electron cloud may be modeled as a broad-band resonator. We write the resonant frequency as:

$$\omega_c = \sqrt{\frac{\pi}{2}} \frac{k}{r_{min}} \tag{3}$$

where $r_{min}=2N_b r_e s_b/b$ is the maximum distance from the beam at which electrons receive sufficient energy in a single bunch passage to reach the wall before the next bunch arrives. Electrons closer to the beam than r_{min} cannot contribute to coherent oscillations in the cloud coupling one bunch to the next.

To estimate the amplitude of the wake field, we consider the kick given to electrons in the cloud on the nominal beam orbit, by a bunch with some displacement from the orbit. This leads to:

$$\frac{cR_s}{Q} = \frac{n_0 s_b}{N_b} \frac{\omega_c}{c} C \tag{4}$$

Decoherence of the oscillations leads to a damping of the wake field characterized by a quality factor $Q \approx 5$. Some parameters for the long-range wake are given in Table 3.

Table 2: Long-range wake parameters.

Quantity	NLC MDR	TESLA
Cloud frequency /s^{-1}	3.4×10^9	1.2×10^8
Wake amplitude /m^{-2}	4.2×10^6	8.7×10^5
Quality factor	5	5

For M equally spaced bunches the frequencies of the different modes are given by:

$$\Omega_\mu - \omega_\beta = \frac{N_b r_e c}{2\gamma\omega_\beta} \sum_{k=0}^{\infty} W_1(ks_b) e^{2\pi i k(\mu+\nu_y)/M}$$

The real part of gives the coherent tune shift, and the imaginary part gives the growth rate of the amplitude of the mode.

Simulations of the long-range wake have been performed for the NLC MDR using the code POSINST [10], which also simulates the build-up of the electron cloud. A comparison between the expected wake with frequency given by (3) and amplitude given by (4), and the results from the simulations, are shown in Figure 3. Note that we use two different values for the cloud density: one given by the neutralization condition, and the other from the simulation. Although the agreement is not exact, it appears that our estimates are of the right order, and we might expect the growth rates that we calculate to be indicative of those to be found in the real machine under the appropriate conditions.

The harmonic number of the NLC MDR is 714. The bunches are arranged in three trains of 192 bunches with every RF bucket within a train filled, and a gap of around 65 ns between the trains. This structure makes it difficult to calculate exactly the modes and their growth rates for a given impedance; for simplicity, we assume that the ring is completely filled with 714 bunches. This is likely to give a pessimistic estimate for the growth rates, which are shown in Figure 4. The fastest growth time is 20 µs. TESLA is a simpler case, since the ring is completely filled with 2830 bunches; the growth rates are shown in Figure 5. The fastest growth time in this case is around 170 µs.

We note that the coherent tune shifts induced by the long-range wake are small, of the order 10^{-3} in both the case of the NLC MDR and the TESLA damping ring.
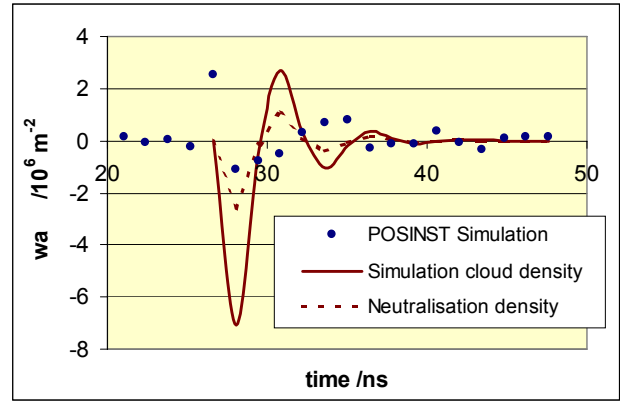

Figure 3: Wake field in NLC MDR from simple analytical model compared with simulation. The points show the simulated wake at successive bunches; the wake is generated by a displaced bunch at 25 ns. (Simulation by M. Pivi)
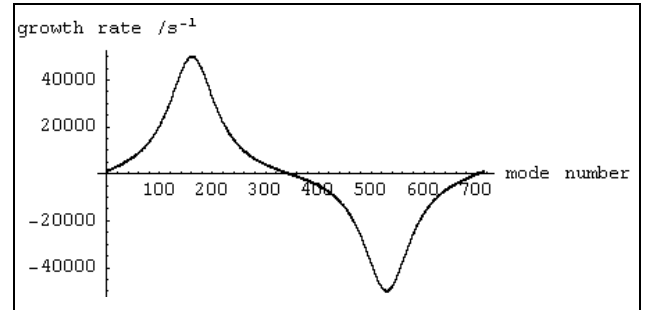

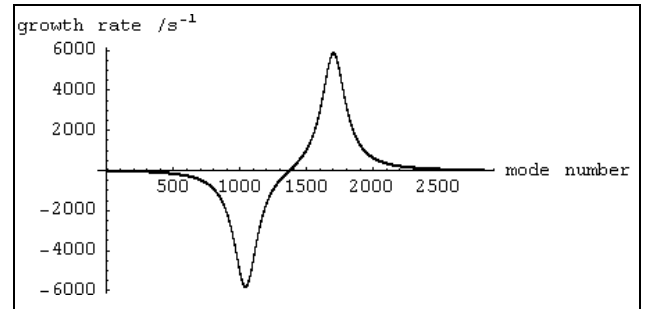Figure 4: Coupled bunch growth rates in the NLC MDR.

Figure 5: Coupled bunch growth rates in the TESLA damping ring.

5 MACHINE COMPARISONS

We have applied the simple models described in the previous sections to the positron storage rings for which the parameters are given in Table 1. In Table 4, we give for each machine the incoherent tune shift, the head-tail threshold impedance divided by the nominal expected impedance, and the fastest coupled bunch growth time. We do not include the density enhancement of the cloud during a single bunch passage, predicted by simulations, so the estimates of incoherent tune shift and head-tail threshold are likely to be rather optimistic.

Table 4: Electron cloud instability thresholds and growth times for some positron storage rings.

	Incoherent Tune Shift	Single Bunch Threshold /Nominal	Coupled Bunch Growth Time /μs
NLC MDR	0.019	0.8	20
NLC PDR	0.003	10	370
TESLA	0.06	2.6	170
KEK-B	0.02	3	180
PEP-II	0.16	0.6	16
DA NE	0.007	6	20
HERA-e	0.006	20	1750

Of the operating storage rings, electron cloud effects have been observed at KEK-B and PEP-II, but not at DA NE or the HERA electron ring. Given that the feedback system for DA NE is capable of damping growth times of the order 20 μs, the results from our simple instability models are in broad agreement with whether electron cloud effects are observed or not. For the damping rings, it appears that the NLC MDR and TESLA are likely to suffer from electron cloud effects, while the NLC PDR may not.

6 CONCLUSIONS

The simple models we have used do not take into account the full complexity of the electron cloud production, dynamics, and interaction with the beam. Nevertheless, the results we obtain are in qualitative agreement with the results of simulations, in the cases where comparisons have been made. The formulae we have used indicate the dependence of the instabilities on beam parameters. The damping rings operate in regimes (high current, small beam size, moderate energy and, in the case of TESLA, large circumference) where electron cloud is likely to be a performance limitation.

More detailed studies, based on a variety of simulations, are needed to give a full understanding, and are in progress. The effects of magnetic fields are known to be important, and have not been included at all in the above analysis. At present, it is expected that use will need to be made of methods to prevent the build-up of electron cloud, e.g. by coating the vacuum chamber with a material that has a low secondary emission yield.

8 REFERENCES

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